Procedures for mitigating safety risks associated with post-blast re-entry times

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ABSTRACT: In this paper, management procedures for post-blast re-entry which offer safety, efficiency and economic benefits to mining operations are introduced. Such management procedures include use of dedicated and inaccessible exhaust airways for directing blast toxic and explosive gases, supported by use of advanced remote atmospheric monitoring technology and automated monitoring. Decrease in post-blast re-entry time with reliable remote monitoring processes and with effective ventilation management procedures results in safer and more efficient mining process and increased production yield. The presented management programs also aid mines in keeping their re-entry practices in compliance with regulatory bodies and company policies. A practical case application is presented to demonstrate the implementation of the program in an operating hard rock mine and evidence actual benefits realized.

1 INTRODUCTION

The potential for incidents relating to the exposure of personnel to blasting fumes during re-entry in underground mines is undoubtedly an area of concern to all. Some mines still rely on the experience of their employees to determine if it is safe for workers to re-enter their mines following blasting; the workers, in turn, merely rely on sight and smell to determine whether a zone is safe to re-enter.

Traditionally, mines use a fixed-time period approach to carry out post-blast re-entry for workers. In re-entry protocols, after a blast, a set period of time must pass before a worker can enter the area and measure levels of toxic gases. This procedure typically takes several hours, directly affecting mine productivity and profits. Using a fixed-time period approach, personnel have to wait until the re-entry time has passed at which point the area is deemed safe. This process is fundamentally unreliable, potentially placing workers at risk of exposure during re-entry. Additionally, although such alternate operational procedures as blasting at the end of shift offer some measure of safety increases, this is again not a foolproof procedure.

Management procedures founded on the use of dedicated and inaccessible exhaust airways for directing blast toxic and explosive gases, and supported by use of advanced remote atmospheric monitoring technology and automated monitoring, offer a safer and more effective post-blast re-entry process. Thuswise, the mining operation workforce will safely re-enter the mine and promptly engage in production activities at the most time efficient way.

2 ESTABLISHING BLAST FUME CONCENTRATIONS AND SAFE RE-ENTRY TIMES

Establishing blast fume concentrations and safe re-entry times is a complex undertaking because of the multitude of controlling factors, and because the behaviour of released blast gases underground is normally inconsistent and unpredictable.

The estimation of the volume of toxic gases released after a blast is dependent upon a number of factors including, the size of the blast including round length and blasthole diameter, the blast design including blast pattern, charge configuration and level of explosive confinement, the mass and types of explosive used, the number of primers used, delay intervals, the rock type and the drift profile. Determining an analytical relationship between the above interdependent variables and the blast fume concentrations released underground during a blast is impractical, if not impossible.

Creating accurate models for establishing safe re-entry times based on the mechanics of fume generation, dispersion and dilution is similarly impractical. The estimation of safe re-entry times after a blast is dependent upon several factors including, the blast design, types of explosive used, the quantity and types of fumes produced, the working face conditions, the ventilation efficiency including duct leakage, reach of fresh air into the face, air velocities, fume dispersion, mixing of airflows and contaminant dilution efficiency, gas layering, fan recirculation, and the amount of fumes entrapped in the muck pile.

The safe re-entry time to a working heading is a function of the volume of fumes liberated from the blast and the rate at which the fumes are diffused by the ventilation system. Even with an optimized blast design, predicting the exact volume of fumes liberated from the blast is practically impossible. For personnel to re-enter a blasted heading, all blast contaminants must be diffused to concentration levels below prescribed limits, not only at the working face but at full length of the route to be travelled by the mining crew. Establishing the optimum time at which re-entry can safely proceed is seemingly impractical.

The application of blast fume management strategies presented in this paper represents an alternate approach which will not only guarantee safety but minimize lost productivity associated with long waiting times.

3 METHODS OF ESTIMATING RE-ENTRY TIMES

An analytical model has been developed by the author (De Souza et al, 1991) for predicting blast gas clearance times for development headings. The model is based on dilution ventilation principles with a logarithmic decay of concentration of contaminants following the blast. Over the years, other authors have added factors to the original model to make it applicable to specific applications.

The original dilution ventilation model was developed for determining the airflow requirements to reduce the contaminant concentrations to prescribed limits and associated re-entry times. The re-entry time prediction model was developed based on the principle that the rate of decrease in contaminant concentration is related to the volume rate of fresh air introduced into the heading.

The required time to reduce a contaminant's concentration to a prescribed limit is determined from,

$$t = \frac{V}{(Q + Q_g)} \ln\left[\frac{(Q_g + QB_g) - (Q + Q_g)x_0}{(Q_g + QB_g) - (Q + Q_g)x}\right] \quad (1)$$

where t = time for the contaminant to reach a prescribed concentration x (sec); V = volume of the working space (m^3); Q = quantity of fresh air supply to the working space (m^3/s); Q_g = inflow rate of the contaminant (m^3/s); B_g = concentration of contaminant in the fresh air supply (decimal); x_0 = concentration of contaminant in the air in the working space at time 0 (decimal); and x = prescribed concentration of contaminant in the air in the working space (decimal).

The volume of the working space, V, is determined based on the volume of contaminant liberated from the blast divided by the peak concentration of contaminant recorded after the blast.

Re-entry times are calculated for one individual contaminant at a time, and consequently the model assumes that the presence of other contaminants does not affect the behaviour and clearance times of each distinctive contaminant. Also, the model assumes that there is no recirculation of contaminants in the ventilation system, it does not incorporate the effect of contaminant densities and the effect of contaminant mixing.

Gillies (Gilles et al, 2004) developed an empirical equation for determining safe re-entry times based on the airflow delivered to development headings, to represent specific conditions in an

Australian base metal mine. The empirical equation was founded on the model developed by De Souza. They substituted recorded maximum values of peak concentration of CO and working volume from a series of tests into De Souza's model and, using regression analysis, correlated the prediction times of De Souza's equation (equation 1) to the actual clearing times of their tests. This resulted in the following empirical equation to predict safe re-entry times in development blasts,

$$Ta = 2{,}383.7Q^{-1.574} \tag{2}$$

where Ta = amount of time required for the concentration of CO to reach its TLV of 30 ppm (min); and Q = the airflow in the development heading (m^3/s).

The authors concluded that the equation was a reliable overestimation of re-entry times for typical development headings in the tested mine, provided that peak CO concentrations of the blast were within a range of 1,120 - 3,000 ppm and based on a working volume of approximately 2,800 m^3. In addition, the airflow in the heading must be above approximately 8 m^3/s and a re-entry time of less than 40 minutes must be predicted for the equation to be valid.

WMC Resources Ltd. (2001) developed an empirical method to predict the fume throwback length, which is then multiplied by the area of the development heading to obtain the working volume for use in De Souza's equation (equation 1) to calculate the blast re-entry time.

The fume throwback length, or the distance from the blast location occupied by the fumes immediately after taking the blast, is given by,

$$L = \frac{KM}{FaD\sqrt{A}} \tag{3}$$

where L = length of fume throwback (m); K = constant, typically 25 but is determined by the type explosive used (unitless); M = mass of explosives used (kg); Fa = face advance (m); D = density of rock (kg/m^3); and A = area of face (m^2).

The fundamental limitation of this empirical method of determining the throwback length and working volume relies upon the certainty of the assumed value of K.

Stewart (2014) introduced a 'dilution efficiency factor' that incorporates the efficiency of duct airflows to penetrate and dilute blast throwback fumes which, once calculated, is applied to De Souza's method (equation 1). The dilution efficiency factor embodies the efficiency of available duct diluting flow to penetrate and clear blast throwback fumes, it empirically accounts for placement, direction and velocity of air from the duct, and also accounts for duct leakage and condition.

The dilution efficiency factor, f_d, is calculated based on field testing, to be then used in De Souza's method to calibrate future estimations of blast clearing times in each specific mine,

$$f_d = \frac{V \ln\left[\frac{G_c}{G_t}\right]}{tQ} \tag{4}$$

where f_d = dilution efficiency factor (unitless); V = volume of gas filled space (m^3); Gc = initial measured maximum gas concentration (ppm); Gt = measured gas concentration at time t (ppm); t = time since blast (s); and Q = flow rate of duct fresh air (m^3/s).

Stewart recommends that, for better accuracy, the estimation of the dilution efficiency factor be based on field measurements at a time when the concentration of CO is 50% of the peak concentration.

Because the behaviour of blast gases is a site specific and complex process, analytical models cannot be solely relied upon to direct mine re-entry time. Alternate and interrelated methods for optimizing re-entry times should be employed as introduced in this paper.

The use of mine network simulations to estimate contaminant clearance over a mine wide ventilation system and to determine re-entry times into main travel ways and active mining areas has also been considered by operators. The many factors associated with specific blast designs and the complex behaviour of blast gases, preclude network modelling being used as a reliable re-entry evaluation tool.

A ventilation management program has been developed to ensure the health and safety of underground workers by creating and incorporating structured Plans, Procedures and Processes for blast re-entry operations. These documents provide guidelines for applying audit, verification and correction processes used to ensure that post-blast re-entry practices operate within compliance standards.

Five main document types form the structure of a ventilation management program: Standards and Guidelines, Codes of Practice, Procedures, Work Instructions and Directives, their relationship being illustrated in Figure 1.

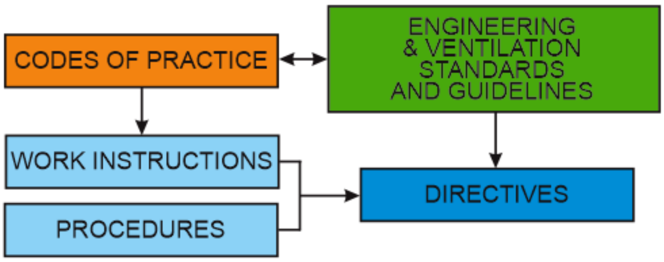

Figure 1. Ventilation Management Program.

The Standards and Guidelines constitutes the foundation of the management program. This support document provides a detailed description of the ventilation system, including all design and operational aspects of the ventilation network. Specifically, it presents re-entry routes, egress routes, locations of refuge stations, ventilation appliances inventory, monitoring and survey instrumentation inventory, system inspections, related regulations, reporting procedures, engineering approval standards and levels of responsibility.

The Ventilation Code of Practice defines the minimum operating standards, it presents administrative and action levels and provides appropriate corrective and emergency action plans when an upset condition exists. Specifically, it presents required air quantities, administrative contaminant levels, auxiliary ventilation systems, re-entry protocols, and responses to fan failure.

Procedures is documentation that explains inter-departmental activities and each department's or individual's role in specific work procedures. Work Instructions is documentation describing the process of a specific procedure and task; including who is involved, how to do the task, and what materials or supporting documentation is needed. Essentially, procedures tell which department does what, and in what sequence and work instructions tell how to do the job. Procedures and work instructions include instrumentation operation, maintenance & calibration, instrumentation installation, daily underground inspections, airflow and pressure surveys, air quality checks and surveys, auxiliary ventilation system design, ventilation system installation, system operation and maintenance, blast design, post-blast re-entry specifications, authorized entry into restricted access areas, mine evacuation, and modelling and simulation. In addition, inspection sheets are developed to ensure consistency in different checkup jobs, and include fan inspection sheets, duct inspection sheets, monitoring station inspection sheets, etc.

Directives is documentation issued for any changes to the ventilation that will ensure the correct installation or change to any design, equipment or condition. Specific procedures and work instructions are attached to a directive in order to give the appropriate instructions on how to correct or change the system. Once at directive is completed the system is inspected to ensure the ventilation system is compliant.

The interrelation of procedures and work instructions is presented in Figure 2. These parameters are discussed in the following sections.

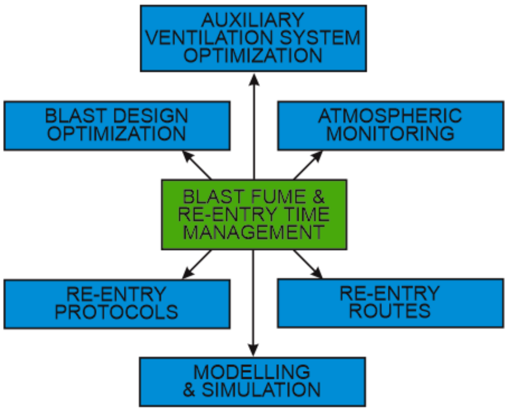

Figure 2. Management Program for Blast Re-Entry Time.

4.1 *Blast Design Optimization*

The first and major precaution against toxic fumes is to control their formation at the source. Several factors affect the concentrations of toxic gas emissions and the types of gases produced during a blast. In particular, poor product formulation will increase gaseous emissions. Thus, when properly formulated and manufactured, the release of toxic gases from explosives and blasting agents will be minimized (De Souza et al, 1993). The chemical composition and the physical nature of an explosive; the type and composition of wrapper; the nature, size and position of primer; and the ambient temperature, all influence the fumes generated by an explosive (De Souza et al, 1991). Other factors that increase the concentration of gaseous emissions include inadequate priming leading to marginal initiation, explosives with insufficient water resistance in wet blast holes, lack of confinement, reactivity of the blasting products with the constituents of the blasted rock, and incomplete product reaction.

By standardizing blast layouts and loading and blast initiation procedures for development and for production blasts, the mine will minimize the variability in fumes produced in each blast, thereby increasing control and reducing blast re-entry times.

4.2 *Auxiliary Ventilation System Optimization*

Dilution ventilation is the primary method of reducing fumes in underground air following a blast. The toxic fumes liberated from blasting operations underground will mix quickly with the ventilation airstream and, if not diluted to acceptable levels, represent potential hazards to the mine environment.

Mixing and dilution of toxic fumes is highly dependent on the quality and effectiveness of the auxiliary ventilation system installation. The effectiveness of an auxiliary ventilation system includes the design flow volume, the duct diameter and air velocity, the installation quality, duct leakage, and the discharge location of the duct from the face.

The discharge airflow from the duct must effectively penetrate the blast fume region and mix with and infuse the blast fumes at the face, and then carry the fumes to the planned return air route. Also, since as much as 60% of the fumes or gases produced during blasting underground may remain entrapped in the muck pile (De Souza et al, 1993), the ventilation system must remain effective during mucking, hauling and dumping operations.

4.3 *Atmospheric Monitoring*

The use of gas monitoring in the underground network is an important tool for the mine operator to not only detect and reduce the risk of hazardous conditions but to reliably estimate the re-entry time.

Modern air quality and gas detection technology can be deployed in strategic locations around the mine ventilation network to provide accurate real-time underground atmospheric conditions, giving the mine critical information for making educated decisions for re-entry that balance health and safety and productivity.

For example, Jahir (Jahir et al, 2016) demonstrated that use of a modular and portable battery-powered wireless gas monitoring system may enable a mine to reduce post-blasting re-entry delays for underground workers.

A vast array of fixed and portable devices is available to detect the concentration of contaminants within the underground mine atmosphere. 'Smart' devices can be integrated into the mine communications network to provide real-time monitoring and diagnostics of the underground environment. Total monitoring stations can be distributed throughout the ventilation network and programmed to automatically relay warnings from anywhere in the underground to a central control room when thresholds in contaminant levels are exceeded. Some devices can be engineered to remotely shut down the affected area, thus eliminating risks to workers.

Every device or station requires frequent calibration to ensure accurate and reliable measurements. The calibration interval is normally specified by the manufacturer but also depends on the site conditions. Mines normally have a dedicated room, fitted with calibration gas cylinders and calibration equipment, for sensor calibration. Regular inspection of every single installation is critical to ensure the devices are in good working order. There have been reported incidents when the safety of workers has been compromised because of uncalibrated and faulty devices (Pike River Royal Commission, 2012; Mason, 2012).

4.4 *Re-Entry Protocols*

Typically, mines follow standard operating procedures for re-entry after blasting. Since such re-entry protocols are primarily developed for worst case scenarios, longer than ideal waiting times will result in costly production delays, undermining the mine's productivity and profitability.

Normally, production blasts, being more energy intensive, are initiated through centralized remote blasting. After the blast is initiated and the local fans have self-started, the gas checking crew enter the mine to measure and record the gas concentrations in the blasted areas with calibrated gas monitors, prior to clearing the areas for re-entry. The lead wire from the blast is short circuited and the check crew enter the area to inspect for any safety hazards. If recorded gas concentrations in the area are below safe limits, the level barricade is removed and the area is cleared for re-entry. In cases where the round fails to detonate, the blasting cap is removed from the main line and the blasted area is barricaded for further action. The gas checking crew will follow a comprehensive gas-clearing checklist as they progress through the mine network.

For development heading blasts, being more localized, stand-alone remote blasting systems are used. After the auxiliary fan has self-started to clear the area of blast contaminants, a visual inspection for any safety hazards and gas level checks are proceeded. Once contaminant levels in the heading fall below safe limits, the area is cleared for re-entry.

The application of re-entry protocols by performing manual atmospheric testing within the mine is not only labour-intensive and time-consuming but ineffective. Because of the dynamic and time-dependent changing conditions in the underground ventilation network, it is impractical to determine the actual time when all areas of the mine are safe. Initiating the post blast re-entry time too early can place the miners at risk of exposure to hazardous contaminants.

4.5 *Re-Entry Routes*

In some mine layouts, access gain to the active levels requires that miners travel through main exhaust airways. For example, in many mines access from the surface is via a main ramp, which in many cases is also used as the main exhaust air route. In other mines, the service shaft may serve as the main exhaust airway. In such cases, accurately establishing the safe re-entry time is essential to eliminate the risk of exposure to hazardous contaminants.

For the above situations, one alternate management program is that of isolation. In some cases, a dedicated secondary exhaust air route can be developed using existing raises. Air ventilating the blasted area is isolated and routed directly to this dedicated route. The primary exhaust air route continues to exhaust vitiated air from other areas of the mine, but is not affected by the blast gases, and still serves as the mine entry route. Re-entry protocols are still employed after the blast. One successful application is presented in the case study.

4.6 *Modelling*

As previously presented, analytical methods cannot accurately determine re-entry times.

The use of mine network simulations to estimate contaminant clearance over a mine wide ventilation system and to determine re-entry times into main travel ways and active mining areas should thus not be used as a reliable re-entry evaluation tool.

Modelling however can be applied to assess the effectiveness of different secondary exhaust air routes for blast gases being considered by the design engineer. Simulation methods can also be effectively used to optimize the route travelled by gas check crews and to identify a safe evacuation route in the event workers encounter contaminants.

5 CASE STUDY

A case study is presented at which post blast re-entry safety has been exceedingly enhanced with the development and implementation of a ventilation management program for an operating underground hard rock mine. A series of occurring minor incidents associated with worker exposure to fumes during post- blast re-entry (in some instances, workers experienced headaches, nausea or dizziness when travelling to the blast area) prompted the mine to take corrective action.

The underground mine applies blasthole stoping to mine gold bearing ore at a rate of 950 tonnes per day. Overall underground flow requirements at the underground production areas approximate 203 m^3/s, determined based on the operating diesel fleet. The mine utilizes a push system with a primary surface air fan installed on a dedicated fresh air raise. A ramp system (Main and East ramps) serves as the primary exhaust route, ore haulage and as the main entry for mine personnel. Figure 3 presents a simplified schematic of the mine ventilation network. Not all levels are shown. The fresh air Alimak raise dimensions are 3.96 m x 3.96 m and the transfer drifts are 4.57 m x 3.96 m. The fresh air raise has a static resistance pressure of 1.92 kPa. The ramp dimensions are 4.72 m x 4.72 m. In some sections of the ramp air velocity reached 4.65 m/s (East ramp) and 5.5 m/s (Main ramp). A series of underground booster fans are used to transfer fresh air to the active levels.

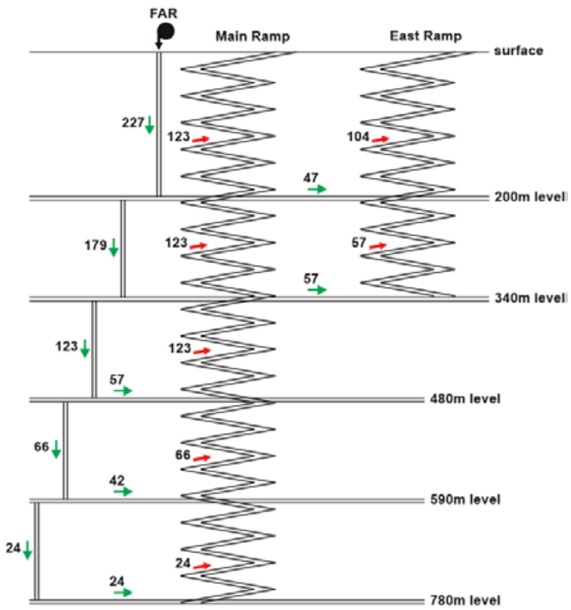

Figure 3. Original Mine Ventilation Network Schematic (flows in m^3/s).

Because entry to the mine is via the main ramp, and because the ramp is the primary route for exhausting air from a blast, fixed gas monitoring stations are installed at critical positions along the ramp. After a blast, gas concentrations remotely measured from the stations together with re-entry protocols followed by gas check crews are used to determine when the mine should be cleared for re-entry. Even with these controls in place, the mine experienced a series of minor incidents associated with worker exposure to fumes during post- blast re-entry.

Investigations indicated that the mine did not follow protocols for scheduled maintenance and calibration of the gas monitoring stations. In many instances, erroneous gas concentrations were being recorded from the stations. Auxiliary ventilation installation and maintenance practices were also inadequate. Poor duct installations resulted in large shock losses and poor system maintenance resulted in excessive air leakage. The air velocity in the duct and the fresh air flow volume exiting the duct were inadequate. In particular, the discharge location of the duct from the face was incorrect and the discharge airflow from the duct was not effectively penetrating the blast fume region and properly diluting the blast fumes.

A management program was implemented, following the measures presented in Section 4. Specific procedures and work instructions were developed for the mine operation, with particular emphasis given to the parameters listed in Figure 2.

The most important modification to the mine ventilation system was the development of a dedicated exhaust air route. Drop raises, 3.5 m x 3.5 m, used during ramp development were used for creation of the parallel exhaust air route, thus construction of the system required minimum capital expenditure. The raise system flow capacity approximates 59 m^3/s. This exhaust raise system is not devised to exhaust the entire mine vitiated airflow but to selectively collect and exhaust air from the blasted area; the ramp system continues to serve as primary exhaust air routes. Figure 4 presents a schematic of the mine ventilation network with the new dedicated exhaust air raise system. In this specific case, the raise is used to selectively exhaust air from a blast at the 480 m level. The reduced exhaust air flow volume, and velocity, at the upper section of the main ramp is noted.

Specific procedures for managing blast gases were developed. Air ventilating the blasted area is isolated and routed directly to this dedicated route. The ramp system does not receive this air but continues to exhaust vitiated air from other areas of the mine and still serves as the mine entry route. Re-entry protocols are still employed after the blast. Procedures and work instructions for scheduled maintenance and calibration of the gas monitoring stations were developed and put into action. Training and procedures for planning and design, installation, operation, inspection and maintenance of auxiliary ventilation systems were implemented and exercised.

Since the implementation of this management strategy the mine not only did meet its safety goals (i.e. to ensure that the workers come home healthy and safe at the end of every shift), with zero post-blast re-entry incident rates, but significantly reduced the time required to clear the blasts (by more than 50%) and notably increased its operational efficiency.

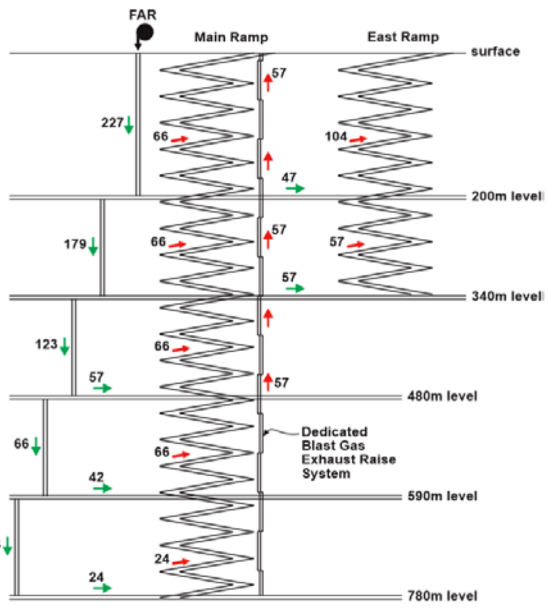

Figure 4. Modified Mine Ventilation Network Schematic (flows in m^3/s).

6 CONCLUSIONS

Management procedures for post-blast re-entry which offer safety, efficiency and economic benefits to mining operations have been presented. The interlinked set of management programs include, - controls at the source using blast design optimization methods, - maximizing dilution ventilation efficiency through auxiliary ventilation system design optimization, - determining optimum re-entry times through use of real-time atmospheric monitoring technology, - establishing standardized re-entry protocols that reduces risk to the gas checking crew, - establishing dedicated secondary exhaust air routes thus removing the risk of blast fume exposure, - applying modelling and simulation techniques to assess the effectiveness of selected exhaust air routes for blast fumes, to assess the safeness of routes travelled by gas check crews and to identify safe evacuation routes.

The presented management programs also aid mines in keeping their re-entry practices in compliance with regulatory bodies and company policies.

The case study demonstrated how the combined application of engineering and administrative controls can be successfully put into effect for safe post blast re-entry in underground mines.

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